# 53 Camelopardalis: a magnetic model consistent with observations of Stokes *I* and *V* profiles

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**Abstract.** We have obtained new observations of Stokes *I* and *V* profiles of the well-known magnetic chemically peculiar (CP) star 53 Camelopardalis, with the spectral resolution $R$ = 40 000, in the wavelength range 5000-6500 Å, at six different rotational phases, and we present a magnetic model accounting for their (periodic) variation. We have adopted the well-established Oblique Rotator Model, which ascribes the variability of the polarized spectra of CP stars to the presence of magnetic fields organized on a large-scale, lacking symmetry around the rotation axis. The magnetic morphology was recovered within the framework of a non axi-symmetric dipole plus quadrupole field, with the help of a recently developed modelling technique based on the combined interpretation of determinations of the longitudinal field, mean field modulus, and broadband linear polarization (taken from published literature). The so-recovered magnetic morphology has been used as input to a newly written code for spectral synthesis, and the synthetic spectra have been compared with the spectropolarimetic observations. The model accounts for strength and shape variation of many spectral lines, although — in agreement with previous spectroscopical studies of this star — we found that the variation in strength exhibited by lines originated by some elements such as Ti and Ca can only be explained in terms of a non-homogeneous element distributions over the stellar surface.

## 1. Introduction

Diagnostic tools for magnetic fields of chemically peculiar (CP) stars of the upper main sequence are mainly based on the detection of those features of the polarized radiation which can be related by means of simple relationships to the stellar magnetic topology.

The theory of line formation in a magnetic atmosphere shows that — under certain assumptions — the analysis of the Zeeman effect on the Stokes *I* and *V* allows determination of some quantities such as, for instance, the mean longitudinal magnetic field, and the mean magnetic field .modulus (see Mathys, 1999 and references therein for a detailed theoretical treatment). The analysis of Stokes *Q* and *U* profiles provides useful constraints to the transverse components of the magnetic field (Mathys, 1999), even when the observations are performed in a broadband filter (Landolfi et al., 1993). In fact, for the modelling purpose, measurements of broadband linear polarization (BBLP) have so far been preferred to observations of linear spectropolarimetry, owing to the noise limitations which often hamper the detection of the magnetic signatures in Stokes *Q* and *U* profiles.

These ***magnetic quantities*** appear to change periodically, with the same period as the stellar rotation (as deduced from photometric measurements). This observed time variation is interpreted in terms of a magnetic field not symmetric around the rotation axis, so that the observer sees a magnetic configuration which changes as the star rotates. The magnetic topology is thought to be organized on a large-scale: solar-like magnetic phenomena would hardly be detected in a spectrum which results from integration over the stellar-disk. Accordingly, it makes sense to attempt a description of the magnetic field with a relatively small number of free parameters.

A technique for modelling the magnetic fields of CP stars has been developed in a recent series of papers (Bagnulo et al., 1996, Landolfi et al., 1999, Bagnulo et al., 2000): the magnetic field is assumed to originate from the superposition of a dipole and a quadrupole field, and its topology is recovered by means of an inversion algorithm which takes into account the constraints given by all the observed magnetic quantities, as well as the projected rotational velocity and stellar radius. Applications of this technique (e.g., Bagnulo et al., 1999, Bagnulo & Landolfi, 1999, Bagnulo et al., 2000) have shown that the magnetic topologies of CP stars usually exhibit non axisymmetric structures, rather different from a simple dipolar topology. Further studies can be of great help in discovering meaningful relationships between the magnetic field morphology and the distribution of the elements over the stellar surface, yielding observational constraints for the diffusion theory.

In fact, the modelling of the observed magnetic quantities is limited by a number of approximations upon which both observational and modelling techniques are based. For instance, the interpretation of Stokes $I$ and $V$ profiles relies on the weak line approximation, which is ***never*** verified in the observed spectral lines. Thus, a comparison of synthetic versus observed Stokes profiles is highly desirable in order to get more insight into the problem of how realistic and reliable magnetic models of CP stars actually are.

The present study represents an attempt to accomplish this step towards a convincing modelling of stellar magnetic fields, presenting a direct comparison of synthetic versus observed $I$ and $V$ Stokes profiles for the well-known magnetic CP star 53 Camelopardalis. Along the lines of a strategy previously suggested by several authors, e.g., Landstreet (1988), Stift & Goossens (1991), and Mathys (1999), we first tried to give a combined interpretation of all magnetic quantities available in the literature, recovering a number of magnetic models that served as input to a spectral synthesis code. The theoretical Stokes profiles were then compared with spectropolarimetric observations obtained at the 1 m telescope of the Special Astrophysical Observatory.

## 2. Observations of 53 Cam

### 2.1. New spectropolarimetry of 53 Cam

18 spectra of Stokes $I$ and V, spanning the range 5000-6500 Å with $R$ = 40000, were obtained during the nights March 6 to 8 1999, April 3 1999 and April 6 to 7 1999, with the Coude Echelle Grating Spectrograph (CEGS) attached to the 1m telescope at the Special Astrophysical Observatory, Russia. The instrumental configuration has been described by Musaev (1996).

### 2.2. Other observational data

For the rotation period we adopted the value of 8.02681 ± 0.00004 obtained by Hill et al., (1998) by means of a first-order Fourier expansion to the observations of the longitudinal field. For the projected rotational velocity Landstreet (1988) estimates $v\sin i$ = $13.0 \pm 1.5\,\mathrm{km\,s^{-1}}$. Landstreet (1988) also provides an estimate for the limb-darkening coefficient ($u$ = 0.575).

With the so-called photographic technique, eight determinations of the longitudinal field were obtained by Preston & Stejneri (1968), and four by Hildebrandt et al., (1997). Borra & Landstreet (1977) made 18 observations of the longitudinal field by means of the $H_\beta$ photopolarimetry. With the same technique, Hill et al., (1998) have obtained 17 new determinations of the longitudinal field.

For the mean magnetic field modulus, we adopted the set of data published by Huchra (1972) and by Mathys et al., (1997). The first measurement of the mean field modulus of 53 Cam was published by Preston (1969), and was also included in our analysis.

53 Cam is the first star to have been monitored in BBLP throughout the entire rotational cycle, when Kemp & Wolstencroft (1974) obtained 32 observations in an extended Johnson $B$ filter. These data were listed by Leroy (1995), who also published 27 other observations obtained by himself in the standard Johnson B filter.

## 3. Modelling of the observations of 53 Cam

We assume that the magnetic configuration of 53 Cam can be approximated with the superposition of a dipole and a quadrupole field, arbitrarily oriented across the (rotating) star. This particular Oblique Rotator Model (ORM), described in Bagnulo et al., (1996) and in Landolfi et al., (1998), generalizes the dipolar model first formalized by Stibbs (1950) to explain the variability of the observations of the longitudinal field observed in most CP stars.

The modelling technique is fully described in Bagnulo et al., (2000). Its application to the data for 53 Cam has led to obtaining about ten different sets of model parameters. All these sets were introduced as input to a code for spectral synthesis (Stift, 1998). For the spectral synthesis, we have taken a stellar atmosphere model calculated with the Kurucz' ***ATLAS*** code, adopting a stellar temperature of 8 500 K and log $g$ = 4.0.

We found that the model with the lowest value of the reduced $\chi^2$ did ***not*** account for our observations of Stokes $I$ and $V$ profiles. A much better agreement was achieved with another model, corresponding to a secondary minimum of the $\chi^2$ hypersurface. Such a model includes a 15 kG dipolar component and a slightly weaker quadrupolar component. It will fully be described in a forthcoming paper.

Our spectral synthesis was carried out throughout the entire observed spectral range. As expected, many spectral lines could not be identified, and for many lines we found inconsistency between the observed

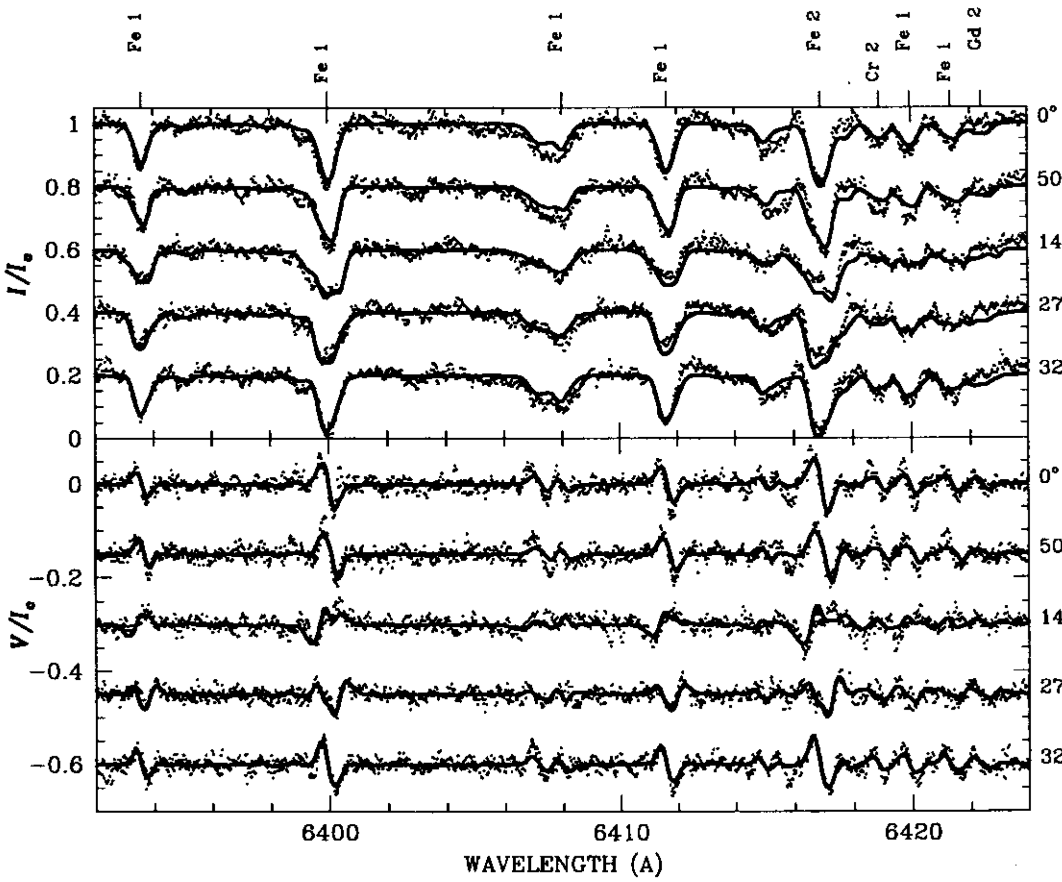


Figure 1: *Synthetic (solid lines) versus observed (dots) Stokes I and V profiles for the CP star 53 Camelopardalis, at five different rotational phases.*

strength and the oscillator strength given in the literature. This is an obvious and well-known problem, and a lot of work is in progress to improve our knowledge of the atomic parameters (Kupka et al., 1999). A typical example of our results is shown in Fig. 1, which shows the model predictions for the spectral lines in the spectral region around 6400 Å. The figure is organized as follows. The upper panel shows the observed Stokes *I* (dots) together with the model predictions (solid lines). The original 18 spectra were grouped in six sets of spectra, each of them observed on the same night; in fact, only five sets are actually plotted in Fig. 1. The relevant (average) rotation phase is indicated on the right side of the plot, and defined according to Bagnulo et al., (1996). The lower panel refers to the *V* profile, and is organized in an analogous way.

It appears that the model adequately represents the observed Stokes *I* and *V* profiles. On the whole, it is clear that the magnetic intensification plays a major role in determining the shape of Stokes *I*, thus caution is required in interpreting shape and strength variation of spectral lines in terms of abundance inhomogeneities. However, it seems very likely that the strong variation exhibited by lines of certain elements (e.g. Ca and Ti) can be explained only in terms of abundances patches.

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